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The ecology of markets

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ABSTRACT Economies are sometimes viewed as analogous to ecological systems in which “everything is connected to everything else.” In complex modern economies, the question arises whether the market mechanism can appropriately coordinate all the interconnections or whether instead some supramarket body is needed to coordinate the vast web of human activities. This study describes how an idealized decentralized competitive market in fact coordinates the different economic organisms in an efficient manner. The problems of pollution and other externalities can undo the efficient outcome unless corrected by appropriate property rights or corrective taxes. But in closing the economic circle, the internalized economy does not actually need to close the natural cycles by linking up all physical flows through recycling.

The term “industrial ecology” is of course a metaphor; some would say it is an oxymoron. Industrial activities are far removed from the swamps, coral reefs, and redwood forests that we usually associate with ecosystems. But the power of the metaphor is that it captures the notion that industrial systems are extremely complex and interdependent. Just as the various parts of an ecosystem are tightly linked through the great chain of eating and being eaten, the modern industrial economy is interconnected through the linkages of resource extraction, production, consumption, and finance.

The notion that “everything is connected to everything else” runs through all of modern economics. Economies are connected in the production sphere through the inputs and outputs that circulate through the world; they are connected through exchange of goods and services; and they are connected by flows of funds through which some people or nations finance the economic activity of others. It is generally believed that the great macroeconomic crises of this century—the periodic banking panics, the Great Depression of the 1930s, the debt crisis of the 1980s, the breakdown in socialist economies of today—occurred because the systems failed, not because of a simultaneous burst of individual economic malfunctions. Furthermore, if some future environmental apocalypse occurs, it will be the result of a failure of markets to incorporate the appropriate signals of scarcity into prices.

Having noted the intricate web of economic activity, I do wonder whether the discussion of industrial ecology and ecological economics is sometimes aimed at the wrong question. The issue is not whether the economy and society are highly interconnected; that is surely true, and the degree of interconnectedness is probably increasing over time. I would agree with Frosch and Gallopoulos, who stated on p. 4 of a paper presented to The Royal Society* that “the industrial system should [be viewed] as an interacting web of inputs, processes, and wastes, all to be thought of together.”

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But complexity is neither necessary nor sufficient for functionality. The fundamental issue is whether the normal economic mechanism will fail to coordinate the interconnected system and whether, therefore, some supramarket body is needed to coordinate the vast web of human activity. This possibility is raised by the suggestion that the level of optimization in current economic organizations is too low and decentralized. In the words of Frosch and Gallopoulos (p. 8)* this possibility is described as follows:

[O]ptimization of a subsystem or a process component does not necessarily yield a system that is optimized overall. This raises the very important and difficult-to-answer question of how large the optimization domain should be. An added complication is presented by the potential conflict between optimization from a mass or thermodynamic sense, and optimization from an economic or environmental or societal sense.

In fact, a great deal is known about the questions raised in this provocative passage. From economic studies of the functioning of a price system, it can be determined when a market system provides the proper coordination of the components. This paper explores some of the ways that economics analyzes the issue of “the ecology of markets” in the sense of interdependence of economic activities. It begins with a historical sketch of the origins of economic analysis of interdependent systems. It then shows the surprising properties of a competitive market economy in the presence of interdependencies. Finally, it indicates the conditions under which market allocations can misfire and lead to economic inefficiency.

Historical Background: The Circular Flow

Any observers of an economy will quickly conclude that there is a great deal of interconnection between the different parts: farmer plants and harvests grain, miller turns it into flour, baker turns it into bread, grocer sells it, and cafeteria worker makes a sandwich for ultimate consumption.

But a deeper look shows that the sequence is in fact circular rather than linear, for the sandwich might be eaten by the original farmer who planted the grain when she visits the Big Apple. The circularity of economic life was described and depicted by Francois Quesnay (1), a physician in the court of Louis XV and a member of the “Physiocrats.” Quesnay likened the circulation of goods in an economy to the flow of blood in the body and developed a theory to describe the way goods and incomes circulate through the economy. Fig. 1 reproduces the version from 1759.

Quesnay’s purpose (1) was to show that agriculture was the only source of wealth in an economy because only agriculture

*Frosch, R. A. & Gallopoulos, N. E. *Toward an Industrial Ecology*, presented to The Royal Society, London, February 21, 1990.

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produced a surplus over the costs of production (perhaps he could be called the patron saint of "deep ecology"). By a surplus, Quesnay meant that the output or net product was in excess of the costs of production; today, this surplus is called "rent" to factors that are fixed in supply. The circular flow starts with 1200 of gross output of agriculture, of which 600 is paid to landlords, who in turn spend half of their income on foodstuffs and half on luxuries and other manufactures from the "sterile" sector. Farmers also buy manufactured goods to replace worn-out capital as well as goods for personal use. Artisans from the industrial sector buy food and trade with other countries, completing the circle of spending and production. Fig. 2 shows the flow of incomes and outputs among the three groups: farmers, "sterile" manufacturers, and landlords.

The contribution of Quesnay's theory (1) was to show the interdependence of economic life. As such, this conception does little to analyze whether the flow of incomes and outputs is efficient or inefficient or to analyze the impact of different conditions on incomes or prices—answers to those questions would have to wait almost 200 years. The limitation of the physiocratic approach is shown by the fact that the central proposition of this approach was to argue that industrial activity is "sterile" because there is no surplus, or economic value over the cost of production. This statement is equivalent to saying that, under competitive conditions and con-

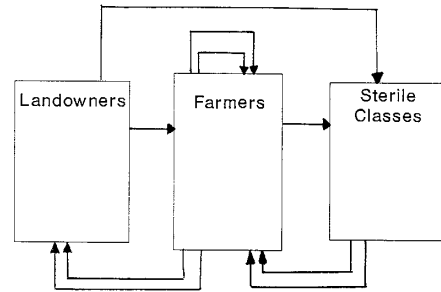


FIG. 2. This modern flow chart represents the *Tableau* of Fig. 1. Each arrow represents a certain flow of expenditure.

stant returns to scale, firms earn no profits. Paradoxically, modern economics turns this proposition on its head by arguing that zero profit is a condition for the efficient operation of a price system.

Input-Output Analysis and Market Allocation

By the middle third of this century, developments in mathematical economics allowed progress in understanding the nature of interdependent systems foreshadowed by Quesnay's theory (1). The tool of input-output analysis, developed by the Russian-born economist Wassily Leontief (2), allows us to write out the industrial ecology of a modern economy in a succinct form. For compactness, let x be a $(n \times 1)$ column vector of gross outputs, let x' be the transpose of x and equal to $[x_1, x_2, \dots, x_n]$, and let y be a vector of final outputs (used for consumption, exports, or new capital goods), where y' is $[y_1, y_2, \dots, y_n]$. The important new concept is the "input-output coefficient," a_{ij} , which measures the flow of good i into the production of good j (units of i per unit of j). The matrix A is a $n \times n$ matrix of input-output coefficients with elements a_{ij} . In addition, we assume that there is some exogenously given primary resource, labor (L), which is used in production. The labor requirement per unit output is b_i , and the vector of labor requirements is $b' = [b_1, b_2, \dots, b_n]$.

We can write the system symbolically as follows (omitting issues of timing for the moment):

$$x \geq Ax + y. \quad [1]$$

$$L \geq b'x. \quad [2]$$

Eq. 1 states that the gross production of each good (the components of x) must be no less than the amount required for the production of other goods (Ax) plus final demands (y). Eq. 2 states that the total labor requirement ($b'x$) must not exceed labor supply (L).

Let us consider this as an industrial ecology by adding some dynamics to the model. Assume in the spirit of Quesnay that inputs of seed, labor, etc., are invested in one period and harvested in the next period. We can then rewrite our system as:

$$x_t \geq Ax_{t+1} + y_t. \quad [3]$$

$$L_t \geq b'x_{t+1}. \quad [4]$$

Say we have millions of farmers, millers, bakers, candlestick makers, and other workers and businesses deciding on their seeding, sowing, and other decisions in an (apparently) completely uncoordinated way. Firms and consumers make decisions completely on the basis of profit and utility considerations, without any intrinsic interest in coordination or in other people's welfare. For simplicity, assume that all

TABLEAU ÉCONOMIQUE.

Objets à considérer, 1° Trois sortes de dépenses; 2° leur source; 3° leur avance; 4° leur distribution; 5° leurs effets; 6° leur reproduction; 7° leurs rapports entr'eux; 8° leurs rapports avec la population; 9° avec l'Agriculture; 10° avec l'industrie; 11° avec le commerce; 12° avec la masse des richesses d'une Nation.

DEPENSES PRODUCTIVES relatives à l'Agriculture, &c.	DEPENSES DU REVENU l'impôt produit, ou partant aux dépenses productives et aux dépenses stériles.	DEPENSES STÉRILES relatives à l'industrie, &c.
Avances annuelles pour produire un revenu de 600. qui sont 600. ^{fr}	Revenu annuel de 600. ^{fr}	Avances annuelles pour les dépenses des dépenses stériles, &c. 300. ^{fr}
Productions, &c. &c.		
300. ^{fr} reproduisent net..... 300. ^{fr}		300. ^{fr}
150. ^{fr} reproduisent net..... 150. ^{fr}		50. ^{fr}
75. ^{fr} reproduisent net..... 75. ^{fr}		75. ^{fr}
37. ^{fr} reproduisent net..... 37. ^{fr}		10. ^{fr}
18. ^{fr} reproduisent net..... 18. ^{fr}		15. ^{fr}
9. ^{fr} reproduisent net..... 9. ^{fr}		6. ^{fr}
4. ^{fr} reproduisent net..... 4. ^{fr}		3. ^{fr}
2. ^{fr} reproduisent net..... 2. ^{fr}		1. ^{fr}
1. ^{fr} reproduisent net..... 1. ^{fr}		3. ^{fr}
0. ^{fr} reproduisent net..... 0. ^{fr}		8. ^{fr}
0. ^{fr} reproduisent net..... 0. ^{fr}		10. ^{fr}
0. ^{fr} reproduisent net..... 0. ^{fr}		11. ^{fr}
0. ^{fr} reproduisent net..... 0. ^{fr}		5. ^{fr}
800. ^{fr}		
REPRODUIT TOTAL 600. ^{fr} de revenu; de plus, les frais annuels de 600. ^{fr} et les intérêts des avances primitives du Laboureur, de 300. ^{fr} que la terre restitue. Ainsi la reproduction ait de 1500. ^{fr} compris le revenu de 600. ^{fr} qui est la base du calcul, abstraction faite de l'impôt prélevé, et des avances qu'exige la reproduction annuelle, &c. Voyez l'Explication à la page suivante.		

FIG. 1. *Tableau Economique* from Quesnay (1). Reprinted with permission from ref. 1 (copyright MacMillan).

participants in an industry face identical technologies and experience "constant returns to scale," so that a μ percent increase in all inputs leads to exactly a μ percent increase in all outputs. Moreover, assume there are no "external effects," or interactions among agents outside of the marketplace.[†]

How well or badly would this "ecosystem" perform? To answer this, we need to consider the costs of production of each firm. For any firm using the technology described in Eqs. 3 and 4, the vector of costs of production at time t , C_t , is:

$$C_t = [A'p_{t-1} + b'w_{t-1}](1 + r_t). \quad [5]$$

In this equation, we write $p' = [p_1, p_2, \dots, p_n]$ as the vector of prices and w as the wage rate per unit labor. We further assume that farmers are charged an interest rate of r percent per period for any borrowings, where the interest rate reflects the productivity of capital or "waiting." The first term on the right hand side of Eq. 5 represents the costs of the inputs of all the different elements (seed, fertilizer, etc.) into the production pipeline; the second term is the unit labor costs; and the term $(1 + r)$ converts incurred production costs into costs in the period when they are sold.

Now assume that there is perfect competition of the multitude of producers. The economic equilibrium occurs when price just covers costs; this is the economic equivalent of a balance between predator and prey or between births and deaths. At equilibrium, we then have:

$$p_t = [A'p_{t-1} + b'w_{t-1}](1 + r_t). \quad [6]$$

For these prices, there will be certain flows of demands, supplies, and inputs satisfying Eqs. 3, 4, and 6 along with the demand relations of the economy.

Now comes the surprise. Under the conditions laid out here, the equilibrium is efficient in the sense of Pareto (3). By "Pareto efficiency," we mean that you could not rearrange the firms, the flows, the production decisions, or anything else to reduce the amount of labor needed to produce the amount of final output actually produced. The actual labor input is the absolute minimum that is needed to produce the vector of consumption goods.

Example 1: This proposition is one of the central results of modern mathematical economics and is the rigorous version of Adam Smith's principle (4) of the "invisible hand." A simplified proof runs as follows.

The first step in the proof is to derive the market solution. The market solution involves the interaction of producers and consumers. For simplicity, assume that all individuals are identical. Individuals are assumed to maximize their level of satisfaction from the final goods, and we represent the satisfaction by a utility function, $U(y)$. Consumers are assumed to own the firms, to share equally in any profits, and to have equal endowments of labor. With m consumers, the k th consumer then owns L/m units of labor and has income of wL/m , which the consumer divides among the various consumer goods, of which the consumer purchases the vector $(y_{1k}, \dots, y_{nk})$, while always respecting the budget constraint $WL/m = p_1y_{1k} + \dots + p_ny_{nk}$. The consumer's optimum condition is easily shown to be $U_i^k/U_j^k = p_i/p_j$, where U_i^k is $\partial U^k/\partial y_{ik}$. This states that the relative marginal utilities of the different goods must be equal to the relative prices.

We noted above that, in perfect competition with no externalities, the competitively determined prices will settle down to the marginal costs, which in this simple case are also equal to average costs. The producer condition will be obtained for the case of a steady state, where all prices, wages, and interest rates are constant. In this case, Eq. 6 can be rewritten as $p = [A'p + b'w](1 + r) = [\phi I - A']^{-1}b'w$, where $\phi = 1/(1 + r)$ and I is the $(n \times n)$ identity matrix. This in fact takes the form of $p_i = \gamma_i w$, where $\gamma = [\phi I - A']^{-1}b'$ and γ_i is the direct and indirect labor content of output marked up by the interest costs.

Combining the producer and consumer equilibria, we obtain:

$$U_i^k/U_j^k = p_i/p_j = \gamma_i/\gamma_j. \quad [7]$$

Next we derive the efficient solution. We assume that society wishes to maximize the level of satisfaction of the representative individual. Omitting certain technical details, we then represent an efficient economy as one in which $U^k(y)$ is maximized given the production constraints in Eqs. 3 and 4. By assuming a steady state, the constraints in Eqs. 3 and 4 can be represented as $L/m = \sum \beta_i y_i$, where $\beta = [\phi I - A']^{-1}b'\sigma$, σ being a technological constant and ϕ again representing the productivity of capital. Without loss of generality, we can set $w = 1$.

This maximization can be represented as

$$\max_{(y_1, \dots, y_n)} U^k(y_1, \dots, y_n) + \lambda^k \left[\frac{L}{m} - \sum \beta_i y_i \right],$$

where λ is a Lagrangean multiplier. The first-order conditions for a maximum are the following:

$$U_i^k = \lambda^k \beta_i = \lambda^k q_i, \quad (i = 1, \dots, n). \quad [8]$$

In these equations, the U_i terms are the marginal utilities of the final goods, the β_i terms are the marginal costs of production, and the q_i terms are new variables that are scarcity values or "shadow prices" that represent the social scarcity of the different goods. The key point of Eq. 8 is that the marginal utilities of the different goods are proportional to the shadow prices and, further, that the marginal costs of production are equal to the shadow prices.

Comparing Eqs. 7 and 8, we see that the solutions are the same because the marginal costs of production for competitive firms (γ) are exactly the same as the (efficient) marginal costs of the final goods to the economy (β). This shows for the simplified case that the competitive allocation is efficient.

A number of the simplifying assumptions can be generalized. There can be differences in tastes, economies out of steady states, insurable risks, capital and time, alternative techniques, and heterogeneous firms without altering the basic result. If there is imperfect competition or if markets do not operate, then the results may not hold. The most important qualification, however, is that there be no externalities, like pollution or information, for which private and social costs diverge.[‡]

The key function of markets is the value (or price) discovery and enforcement mechanism. That is, the ideal competitive market discovers the value of goods to consumers and the costs of production to firms. The key tool in value discovery is the price, which is the carrot and the stick of a market. I call the optimally determined prices "shadow prices" to indicate that they are prices that represent mar-

[†]This innocuous assumption is crucial to the argument that follows. Envision all of the artisans operating their plot of land with no technological interactions such as fish pollution or honeybee pollination. The only way they interact is when they come to market and buy or sell their bee honey or fish.

[‡]Although Adam Smith (4) described the efficiency of markets in his famous "invisible hand" metaphor, the first economist to describe the conditions under which a competitive market is Pareto efficient was E. Barone (5). The first rigorous proof is generally ascribed to K. J. Arrow (6). A thorough survey is contained in K. J. Arrow and F. Hahn (7).

ginal costs and marginal utilities and to indicate that they may diverge from market prices.

The Ecology of Markets. What is this idealized story telling us about the ecology of markets? It says that there is a coordinating mechanism at work above the level of the individual economic organism. That function is being performed by prices, which signal the marginal value of goods to consumers and the marginal cost of goods to producers. In a competitive market, there is no need for a supercomputer or central planner to try to optimize the entire system, accounting for all the trillions of interactions among the different economic organisms, for the prices are providing the appropriate economic signals. As social engineers, we can allow each little firm and consumer to wander through the thicket of input-output relationships without our needing to worry about any interactions with other organisms as long as those interactions take place through the marketplace.

This result has a surprising corollary: In our idealized market economy, the usual efficiencies that are staple for physical scientists have no independent claim to virtue. As social engineers dedicated to the pursuit of human satisfactions, we need not fret about thermodynamic constraints or thermal efficiency or the extent to which we are adding to the universe's entropy.⁸ These physical constraints will be important only to the extent that they enter into the shadow price of particular resources. Put differently, it is not sensible to minimize the BTU input ($1 \text{ BTU} = 1.055 \times 10^3 \text{ J}$) into a production process; rather, we should minimize the BTUs after each BTU is weighted by the appropriate shadow price on that BTU.

This panegyric to the market seems to prove the Panglossian view that a world of markets is the best of all possible worlds. But it leaves out a number of real world features that cast doubt on the conclusions. What if there are nonrenewable energy or other natural resources that the economy is exhausting? What about the growing landfills, the ozone hole, and the threat of climate change? What about the issues concerning equity of the market allocation? Where are the depressions that have thrown millions out of work or the hyperinflations that have destroyed currencies? I deal briefly with equity and macroeconomic disturbances and in the balance of this paper turn to issues of resources and pollution.

Income Distribution. Forget for the moment about market failures of monopolies, pollution, and so on. What do ideal competitive markets mean for the distribution of income? Is there an invisible hand in the marketplace that ensures that the most deserving people will obtain the just rewards or that those who toil long hours will receive a decent standard of living?

No. In fact, competitive markets do not guarantee that income and consumption will necessarily go to the neediest or most deserving. Rather, the distribution of income and consumption in a market economy reflects initial endowments of inherited talents and wealth along with a variety of factors such as discrimination, effort, health, and luck. Therefore, whatever a market may do to promote efficiency, Adam Smith (4) was not wholly justified in asserting that an invisible hand successfully channels individuals who selfishly seek their own interest into promoting the "public interest"—if the public interest includes a fair distribution of income and property. Smith proved nothing of this kind, nor has any economist since 1776.

Macroeconomic Disturbances. For at least two centuries, market economies have been plagued by periodic bouts of inflation (rising prices) and depression (high unemployment). At times, as during the Great Depression of the 1930s,

hardship persisted for a decade because governments did not yet know how to revive the economy.

This branch of economics, known as "macroeconomics," was neglected until the seminal contribution of J. M. Keynes (9). Today, economists generally believe that certain frictions and rigidities in markets—particularly, those due to inflexible wages and prices—lie behind the temporary deviations of economic activity from its full potential. Macroeconomic disturbances probably produce losses in output that exceed the wastes from pollution and monopoly, but that is another story for another day.

Natural Resources, Wastes, and Equity

Return now to our central theme of the efficiency of a market economy. A modified circular flow is shown in Fig. 3. Here we have the original circular flow inside the larger box called "industrial activity." In addition, however, there is a fixed supply of energy and natural resources that are being drawn upon by industrial activity. And there are wastes that are being dumped. This differs from the circular flow and the ecological metaphor because it is not a closed system from a physical point of view. Resources are definitely being drawn down and wastes are definitely being accumulated.

Natural Resources and Energy. So far, our analysis of the ecology of markets has described a circular flow of economic activity in which the only external factor was labor. What happens if we extend the analysis of market behavior to include depletable natural resources? This question has a long intellectual history in economics. One of the earliest studies was by the distinguished British economist William Stanley Jevons, a founder of the theory of marginal utility. Jevons (10) took a rather optimistic view of the role of coal: "Day by day it becomes more evident that the Coal we happily possess in excellent quality and abundance is the mainspring of modern material civilization." This rosy view should be compared with the gloomy views on resource exhaustion presented by Meadows *et al.* (11) or assessments of the impact of continued coal use on climate change (for a scientific assessment of the policy issues, see ref. 12).

Let's pose the issue sharply: Would we expect that a market system would use exhaustible natural resources too rapidly? In terms of pricing, this is equivalent to asking whether the market price of natural resources is set too low. We can answer this question by extending the earlier analysis of efficiency and markets to include a single natural resource.

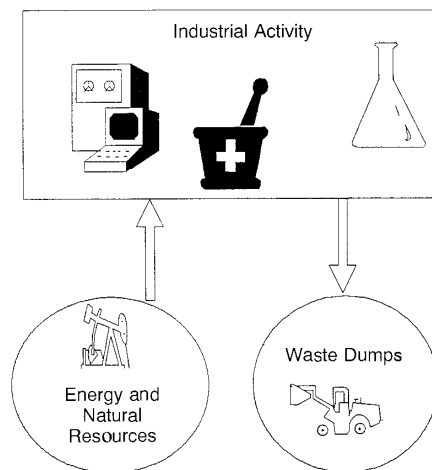


FIG. 3. Ecology of markets.

⁸This would cast doubt on entropy theories of value, such as the eloquent disquisition on the constraints due to entropy contained in the works of N. Georgescu-Roegen, especially in ref. 8.

Table 1. Optimal production of natural gas and solar energy and efficiency prices of fuels (per 25-year period)

Period	Amounts produced and used, billions of units		Discounted costs of optimal program, billions of discounted \$	Efficiency prices of fuels, constant \$ per unit	
	Gas	Solar		Solar	Gas
1	325	0	325.0	$q_{s,1} \leq 6.0$	$q_{g,1} = 1.0005$
2	325	0	32.5	$q_{s,2} \leq 6.0$	$q_{g,2} = 1.005$
3	325	0	3.25	$q_{s,3} \leq 6.0$	$q_{g,3} = 1.05$
4	325	0	0.325	$q_{s,4} \leq 6.0$	$q_{g,4} = 1.5$
5	200	125	0.095	$q_{s,5} = 6.0$	$q_{g,5} = 6.0$
6	0	325	0.0195	$q_{s,6} = 6.0$	$q_{g,6} \geq 6.0$
Total	1500	450	361.1895		

Assume that there is a single low-cost, limited, and clean energy source (call it natural gas or G). When G is exhausted, the economy's energy needs must be met with a high-cost, clean, and superabundant resource, sometimes called a "backstop technology," which we can call solar energy or S . The two forms of energy are assumed to be perfect substitutes in production. All markets are perfectly competitive, and there are no distortionary taxes, uncertainties, or externalities.

Under these conditions, it can be shown that the market will allocate the scarce natural resource efficiently. This implies that the quantity of the scarce resource allocated to each time period and demand category will be put to its most valuable use; no planner could find a way to reallocate the resource in a way that would raise the satisfaction or consumption in any period without lowering these in another period.

Putting this proposition in yet another way, there is no way to produce the consumption enjoyed by the economy with fewer inputs of natural gas and other resources.

Example 2: We use a different kind of proof for this proposition, relying on the theory of linear programming developed by L. V. Kantorovich (13) and T. C. Koopmans (14). The efficient allocation is one that minimizes the costs of meeting a given list of energy services. We write this as a linear programming problem in which we minimize the discounted costs of the energy services subject to the availability constraints. Assume that there are 1500 units of G , that the amount of energy required each 25-year period is 325 units, and that for simplicity of calculation the 25-year discount rate on future costs is $(1 + r)^{-25} = 0.1$. Finally, assume that the cost of gas is \$1 per unit whereas the cost of solar energy is \$6 per unit.[†]

The efficient allocation of resources is one that minimizes the present value of energy costs, V :

$$V = 0.1^0(G_1 + 6S_1) + 0.1^1(G_2 + 6S_2) + 0.1^2(G_3 + 6S_3) + 0.1^3(G_4 + 6S_4) + \dots + 0.1^{n-1}(G_n + 6S_n). \quad [9]$$

Here G_t is the quantity of gas produced and consumed in period t and S_t is the quantity of solar energy produced and consumed in period t . The cost is simply the quantity of the fuels used in each period times their costs, discounted back to the present.

The production requirement is that the total energy production is at least equal to the energy requirement for each period:

$$G_t + S_t \geq 325, \quad \text{all } t. \quad [10]$$

In addition, the total amount of gas extracted must be no more than the resources, so:

$$G_1 + G_2 + \dots + G_n \leq 1500. \quad [11]$$

The only difficulty with this problem is that all variables must be nonnegative, which rules out classical calculus as a solution technique. The solution is straightforward using the technique of linear programming. (The proof that this is actually the efficient program is omitted but is analogous to the proof in the last section.)

The solution is given in Table 1. The second and third columns show the use of the inexpensive fuel and of the expensive backstop technology. Not surprisingly, the less expensive fuel will be used first because of the effect of discounting. Then when the gas is exhausted, the economy turns to the more expensive energy source. The first four periods use the low-cost fuel exclusively. In the fifth period, gas cannot meet the entire need, so a blend of gas and solar energy is used. In the last period, the economy relies exclusively on the solar backstop technology. We have looked only at the first six periods, but it can easily be seen that the solution would be the same if the reference period were 8, 10, or a million periods.

An intriguing further aspect of the efficient program can be displayed using the notion of "efficiency prices," which are the same as the "shadow prices" used in example 1. A precise definition of the shadow price of a good is the decrease in the objective function (i.e., the decrease in cost) that comes from a one-unit change in one of the activities or constraints. In particular, we examine the shadow price on one of the fuels delivered at some future period (and then translate that into current values instead of expressing them as present values). For example, the shadow price of natural gas in period 1, $q_{g,1}$, is the amount that the total cost would decline if an additional unit of delivered gas were to be made available for $t = 1$. It can be thought of analytically as the derivative of the cost function with respect to deliveries of that particular fuel. If an additional unit of natural gas were to be made available in period 1, the cost of meeting the energy demands would go down by \$1.0005. Interestingly, the shadow prices of natural gas increase over time (in constant dollars at the time of delivery).

The shadow prices seem a strange bird in our ecological economy. But, as Kantorovich (17) argued in the late 1930s, shadow prices play a crucial role in helping to determine an efficient allocation of resources in a planned economy. Indeed, in his view an optimal plan cannot be separated from its prices. He showed that if individual decision makers (consumers and firms) make decisions on the basis of the shadow prices, the central planners can completely decentralize the major economic decisions. Many Soviet economists believed until recently that improvements in the central-planning mechanism could come from introducing the linear programming technique and prices into the Soviet economy—although that hope has now generally been abandoned.

Notwithstanding the collapse of the dream of central planning, shadow prices play a crucial role in thinking about

[†]More detailed approaches to this are provided refs. 15 and 16. The example that follows is adapted from these works.

economic efficiency for they represent the value of a resource or activity to the economy. In cases of market failure, such as in the public-goods example given below, the shadow prices will be critical to repairing the market failure.

Market Solution. Turn next to examine the market solution. The basic constraints are the same as above, but the criteria facing decision makers differ. In the market economy, individuals or firms own the energy resources, and they hold them or use them depending upon the prices that are expected to prevail. For simplicity, we assume that the future is known with certainty. Then solar energy has a supply price of \$6, with no supply forthcoming at a lower price and indefinitely large amounts available at that price.

For natural gas, the decision is a bit more complicated. Owners of gas can either sell it at the market price of $p_{g,t}$, yielding a net revenue of $p_{g,t} - 1$, where 1 is the extraction cost. Or they can hold on to the gas for a period and make a capital gain. Define the royalty as the net revenue, $p_{g,t} - 1$. The equilibrium condition for the owner of the gas is that

Rate of return on holding gas from period t to period $(t + 1)$

$$\begin{aligned} &= (p_{g,t+1} - p_{g,t}) / p_{g,t} \\ &= \text{rate of return on alternative assets} \\ &= R_t, \end{aligned} \quad [12]$$

where R_t is the rate of return over the relevant time period (call it the rate of interest). Eq. 12 says that gas owners will hold the gas from one period to the next only if they expect the net value of the gas to rise at least at the rate of interest; if the royalty rose less than the rate of interest, all the gas would be sold. If the royalty rose more quickly, on the other hand, no gas would be sold. Therefore, to sell some but not all the gas (that is, for "stock" equilibrium), the royalty must rise at a rate exactly equal to the rate of interest.

What does that imply for the price? Let's say that the price in period 1 is 1.0005. The royalty is, therefore, $1.0005 - 1 = 0.0005$. In the next period, the royalty will be $0.0005 \times (1 + r)^{25} = 0.0005 \times 10 = 0.005$, and the price is, therefore, 1.005. Moreover, in the period in which gas is exhausted and solar energy just begins to enter the market, the price of gas equals 6. In fact, the price trajectory is exactly the trajectory shown in the last column of Table 1. That is, the price of an exhaustible resource in competitive markets is exactly equal to the efficiency price generated by an efficient use of the resource.

The model is drastically oversimplified but can be extended to include many energy resources, demands, regions, consumers, and technologies. As long as the resources are owned and the markets are complete and competitive, the market outcome is efficient.

Externalities: Pollution. We have shown that well-functioning markets are able to allocate exhaustible natural resources efficiently. This result extends to other kinds of natural resources, including agricultural land, forests, non-fuel minerals, arsenic, heavy metals, negentropy, and so forth. But we must be careful not to push these results too far. They do not, as this section shows, extend to activities that generate what are known as externalities (or spillover effects), which occur when firms or people impose costs or benefits on others outside the marketplace.

The notion of externality is complicated and can be usefully compared with a normal economic good. Market transactions involve voluntary exchange in which people exchange goods for money. When a firm uses a scarce resource like land, oil, or wheat, it buys the good from its owner, who is fully compensated for the incremental costs of production of the good, as we showed above. But many interactions take

place outside markets. Firm A dumps a toxic chemical into a stream and fouls the stream for people who fish or swim downstream. Firm A has used the scarce clean water without paying people whose water is fouled and has generated an external diseconomy. Many activities generate external economies. Firm B invents a new microprocessor that is easily cloned; it captures part of the social return to its inventive activity, but a large benefit accrues to consumers in the form of lower prices and improved services. In both cases, a firm has helped or hurt people outside the market transactions; that is, there is an economic transaction without an economic payment.^{||}

The existence of externalities generates a fundamental flaw in the market mechanism. In the presence of externalities, markets provide incorrect signals to firms and consumers and generate inefficient prices and outputs. Generally, markets produce too much of goods that generate external diseconomies and too little of goods that produce external economies.

Example 3: This point will be illustrated by a simple example. Assume that a particular good is produced with average cost and marginal cost of \$1 per unit. There are n individuals who purchase the good. Each individual buys g_i of the good and enjoys G_i of the good; g_i differs from G_i because there are spillovers and some of other people's purchases affect an individual's satisfaction. We represent the satisfaction enjoyed by consumer i (in monetary units or money-metric utility) as:

$$u^i = \log(G_i), \quad [13]$$

where u^i is the utility function or satisfaction index of individual i . We take $u(\cdot)$ to be logarithmic for ease of computation. The new twist now comes in the amount of the public good enjoyed by the individual. Because the good has "public good" characteristics, the individual gets some enjoyment from the purchases of other people. This is given by

$$G_i = g_i + \mu \sum_{j \neq i} g_j = g_i + \mu(n-1)g_{i,j}, \quad [14]$$

where $g_{i,j}$ is the mean of the g terms for all individuals except the i th individual. The new feature is the parameter μ , which is the spillover factor. For $\mu = 0$, the good is a pure private good, like bread, where my eating a slice produces no utility for you. At the other extreme are "public goods," like national defense or pure science, of which all people consume exactly the same amounts.

First examine an efficient allocation. Assume that all individuals are identical and that the desideratum is to maximize the sum of satisfactions. Then the optimal allocation is:

$$\begin{aligned} \max W(g_1, \dots, g_n) &= \max \sum_i u^i(G_i) - \sum_i g_i \\ &= \max \sum_i \log(G_i) - \sum_i g_i, \end{aligned} \quad [15]$$

which leads to the following first-order conditions:

$$W_i = 1/G_i + \sum_{j \neq i} \mu/G_j - 1 = 0. \quad [16]$$

^{||}External diseconomies like pollution get most of the press about externalities. Economic history suggests, however, that external economies in the generation of knowledge through science, research, and development have been quantitatively more important than the diseconomies. A series of careful studies of the returns to research and development by Mansfield (18), Nathan (19), and others (20) determined for a large sample of innovations that the social return to those innovations was nearly 50% per annum as compared to the private return of around 15% per annum.

The symmetric equilibrium comes where

$$g_i = 1.$$

$$G_i = 1 + \mu(n-1). \quad [17]$$

In other words, the efficient allocation is for each individual to buy one unit of the public good, although because of the spillover the individual satisfaction will be considerably larger [by the factor $1 + \mu(n-1)$].

The market solution has each individual maximizing his or her own satisfaction, giving no weight to other individuals—homo economicus is a species in which natural selection has bred no altruistic genes! Thus the individual maximizes

$$\max_{(g_i)} [u^i(G_i) - g_i] = \max[\log(G_i) - g_i], \quad [18]$$

which leads to the following first-order conditions:

$$u^{i'}(G_i) - 1 = [g_i + \mu(n-1)g_{i,j}]^{-1} - 1 = 0. \quad [19]$$

The symmetric noncooperative equilibrium comes where

$$g_i = 1/[1 + \mu(n-1)]. \quad [20]$$

$$G_i = 1.$$

The important point is to note the ratio of consumption in the market and efficient cases, derived from Eqs. 17 and 20:

Ratio of production in efficient to market equilibrium

$$= 1 + \mu(n-1). \quad [21]$$

Eq. 21 states that the total production of public goods will be larger than the total production of private goods as determined by the amount of spillover (μ) and by the number of people involved (n). For the pure private good ($\mu = 0$), the two equilibria coincide, showing once again the efficiency of the market solution. However, if there are spillovers, the market solution generates too little of the public good. For large spillovers and large numbers of people, the market can be enormously inefficient. For example, we might ask how much abatement of greenhouse gases would occur in a market solution. Because climate change is a pure public good involving billions of people, it is likely that the market-driven spending to slow climate change would be literally orders of magnitude less than an efficient outcome.

The analysis speaks of "public goods." It applies equally well to pollution and other "public bads" by simply changing the sign. Thus if we think of abatement as negative pollution, the result applies to abatement activities; it implies that a market will generate too little abatement and, therefore, too much pollution.

Remedies for Externalities. Because pollution and other externalities give rise to inefficiencies, governments are often called upon to correct the market failures. Virtually all efficient solutions involve "internalization," which denotes facing individual decision makers with the total social costs or benefits of their actions. One example is legal liability, wherein someone damaging others can be forced to compensate the injured parties for damages.

The most difficult and controversial government remedies come in the area of environmental controls. For the most part, governments have relied upon "command and control" approaches, instructing polluters to desist from or control certain activities. Economic studies indicate that these ap-

proaches can be enormously inefficient.** Because of the inefficiency of existing approaches, economists have emphasized the usefulness of "incentive" or "market" approaches to externalities. Under this approach, the generator of the externality would face externality taxes or subsidies so that the price signal would reflect the total social cost or benefit rather than the private cost or benefit that would occur in an unregulated market with externalities.

The remarkable result is that by levying the appropriate externality tax or subsidy, a market will generate the efficient outcome.

Example 4: A proof can be sketched using example 3. Say that a careful study of the technology and public good has determined that there are uncompensated external costs from air pollution. An accounting indicates that the ratio of social benefits to private benefits of abatement $[1 + \mu(n-1)]$ is 150%. The government then levies a pollution charge of 50% of the private cost. This transforms the individual problem into:

$$\max_{(g_i)} \{u^i(G_i) - [1 + \mu(n-1)]^{-1}g_i\}$$

$$= \max\{\log(G_i) - [1 + \mu(n-1)]^{-1}g_i\}, \quad [18a]$$

which leads to the following first-order conditions:

$$u^{i'}(G_i) = [g_i + \mu(n-1)g_{i,j}]^{-1} - [1 + \mu(n-1)]^{-1} = 0, \quad [19a]$$

which in equilibrium produces exactly the efficient solution in Eq. 17.

This shows the impact of imposition of pollution taxes, sometimes called "Pigovian taxes" after the Cambridge economist A. C. Pigou, who first analyzed and proposed them (22). This analysis is intimately related to the earlier examples, for the Pigovian taxes are designed to correct market prices by turning the market prices into social shadow prices of the public-good activity. In other words, after the appropriate correction is made, the market prices are once again efficiency prices, and the market agents can again be relied upon to make allocational decisions in the secure knowledge that these decisions will lead to efficient outcomes.

This solution to the pollution problem is elegant and intellectually satisfying, but to date it has generated about as much excitement among legislators as has cold fusion among physicists. The only practical example of externality taxes to date are the taxes on chlorofluorocarbons, passed in 1989. These levy taxes in proportion to the ozone depletion potential of different chemicals and meet the important cost-effectiveness test for control strategies. An important proposal in the area of climate change is the carbon tax, which would tend to equalize the marginal costs of abatement in different uses as a way of slowing global warming. The recent National Academy panel on greenhouse warming (23) proposed the study of "full social cost pricing of energy," which would implement imposing externality taxes or fees reflecting the externalities of energy use.††

In fact, there are severe impediments to implementing externality pricing in most circumstances. The fundamental difficulty is that, unlike conventional markets, there is no value discovery mechanism for externalities. There is no bidding that discovers the costs and value of abatement or new environmental technologies of the kind that exists for

**A survey by Tietenberg (21) has found that command and control regulations might cost many times more than an efficiently designed regulatory strategy.

††A thoughtful analysis of the advantages of market-like devices as efficient approaches to pollution control is contained in ref. 24. The latest proposal is contained in ref. 23.

natural gas and computers.^{‡‡} This leads to the difficulty of determining the appropriate taxes or fees. There is no market in which the externalities are priced, nor are the measurements of the damages readily made. In many cases, estimates of damages from environmental hazards differ by an order of magnitude. Another difficulty arises from the heterogeneity of the "output." The actual damages from air pollution will vary continuously depending upon the location, time, and weather conditions, and the difference for a pollutant like sulfur might vary by a factor of 10,000 (see ref. 25).

In addition, there may be technical requirements where production of the public good entails a "natural monopoly," in which production is much more efficient in a single producer than in workably competitive markets. Even if it were possible to calculate the appropriate shadow prices for national defense, it would be hopelessly inefficient to privatize the provision of national defense services.

Ecological Idyll Regained. Notwithstanding the practical difficulties that arise in implementing externality pricing, the logic of these fees is that they turn the economy into the economic equivalent of a closed ecological system. That is, by ensuring that all costs and benefits are priced at full social costs and benefits, the circular flow of the economy is closed. The internalized system once again will squeeze the maximum human satisfaction out of the limited human and natural resources at its disposal.

In closing the circle, the internalized economy does not actually need to close the physical cycle by connecting the waste dumps with the energy resources in Fig. 3. There is no need to recycle all the garbage or incinerate all the trash; it would be wasteful to require zero emissions or 100% recycling. Moreover, the notion of running the economy solely on renewable resources is no more sensible than bulldozing the houses to allow the forest primeval to regenerate. The economy will be transformed over time as it moves from charcoal to coal to oil to some future fuel. Nor is there any

need for an overarching intelligence or Gosplan or EPA to organize the components and give directives to individual firms and consumers. If the major externalities can be corrected (a very big if!), then the carrots and sticks of profits and losses will do for human societies what an idealized Darwinian natural selection will do for ecosystems.

^{‡‡}As an example, take the "market mechanism" that was designed in the 1990 Clean Air Act for reducing the emissions of sulfur. The Act envisions creation of tradable permits for emissions among firms. This will allow one part of the value discovery—that pertaining to the costs of production—because in principle firms will trade permits so that the marginal costs of emission reductions are equalized. There is no similar mechanism on the consumer side, however. Hence, there is no guarantee that the marginal value of the emissions reductions will be close to the marginal costs of those reductions. From a practical point of view, the difficulty of discovering the value of emissions reductions is an unsolved problem today.

1. Quesnay, F. (1972) *Tableau Economique, 1758–59 Editions*, eds. Kuczynski, M. & Meek R. L. (MacMillan, London).
2. Leontief, W. (1951) *The Structure of the American Economy* (Harvard Univ. Press, Cambridge, MA).
3. Pareto, V. (1909) *Manuel d'Economie Politique* (Giard, Paris).
4. Smith, A. (1776) *The Wealth of Nations* (Strahan & Cadell, London).
5. Barone, E. (1908) *G. Econ.*, pp. 267–293 and 391–414.
6. Arrow, K. J. (1951) *Proceedings of the Second Berkeley Symposium on Mathematical Statistics and Probability*, ed. Neyman, J. (Univ. of California Press, Berkeley), pp. 507–532.
7. Arrow, K. J. & Hahn, F. (1971) *General Competitive Analysis* (Holden Day, San Francisco).
8. Georgescu-Roegen, N. (1971) *The Entropy Law and the Economic Process* (Harvard Univ. Press, Cambridge, MA).
9. Keynes, J. M. (1936) *The General Theory of Employment, Interest and Money* (Harcourt Brace, New York).
10. Jevons, W. S. (1866) *The Coal Question* (Routledge, London).
11. Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. H. (1972) *The Limits to Growth* (Universe Books, New York).
12. Intergovernmental Panel on Climate Change (1990) *Scientific Assessment* (Cambridge Univ. Press, Cambridge, U.K.).
13. Kantorovich, L. V. (1940) *Doklady* **28**, 211–214.
14. Koopmans, T. C. (1951) *Econometrica* **19**, 455–463.
15. Nordhaus, W. D. (1979) *The Efficient Use of Energy Resources* (Yale Univ. Press, New Haven, CT).
16. Gordon, R. B., Koopmans, T. C., Nordhaus, W. D. & Skinner, B. J. (1987) *Toward a New Iron Age? Quantitative Modeling of Resource Exhaustion* (Harvard Univ. Press, Cambridge, MA).
17. Kantorovich, L. V. (1940).
18. Mansfield, E. (1968) *Industrial Research and Technological Innovation* (Norton, New York).
19. Griliches, Z. (1958) *J. Political Economy* **66**, 419–431.
20. National Science Board (1977) *Science Indicators 1976* (Govt. Printing Office, Washington).
21. Tietenberg, T. (1988) *Environmental and Natural Resource Economics* (Scott Foresman, Glenview, IL), 2nd Ed.
22. Pigou, A. C. (1932) *The Economics of Welfare* (Routledge, London).
23. National Research Council (1991) *Policy Implications of Greenhouse Warming* (Natl. Acad. Press, Washington).
24. Schultze, C. L. (1975) *The Public Use of the Private Interest* (Brookings Inst., Washington).
25. Mendelsohn, R. (1980) *J. Environ. Econ. Manage.* **7**, 30–43.